A 13-Year Time Series of Photosynthetically Available Radiation over the World Oceans from SeaWiFS and MODIS Data

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1. INTRODUCTION

-Photosynthetically Available Radiation (PAR) is defined as the quantum energy flux from the Sun in the spectral range 400-700 nm. It is expressed in Einstein/m^2/day. Daily PAR is the average flux during a day (24 hours).

-PAR controls the growth of phytoplankton and, therefore, the development of crustaceans, fish, and other consumers.

-It ultimately regulates the composition and evolution of marine ecosystems.

-Knowing the distribution of PAR over the oceans, spatially and temporally, is critical to:
•Understanding bio-geo-chemical cycles of carbon, nutrients, and oxygen, and
•Addressing climate and global change issues, such as the fate of anthropogenic atmospheric carbon dioxide.

2. SATELLITE ESTIMATION

-PAR is computed as the difference between the 400-700 nm solar flux incident on the top of the atmosphere (known) and reflected back to space by the atmosphere and surface (measured), taking into account atmospheric absorption (modeled).

-Knowledge of pixel composition is not required, eliminating the need for cloud screening and arbitrary assumptions about sub-pixel cloudiness.

Model

-The PAR model uses plane-parallel theory and assumes that the effects of clouds and clear atmosphere can be de-coupled. The planetary atmosphere is therefore modeled as a clear sky atmosphere positioned above a cloud layer.

-The solar flux reaching the ocean surface is given by

$E = E_{clear}(1 - A)(1 - A_s)^{-1}$

where A is the albedo of the cloud-surface system and A_s the albedo of the surface.

-$E_{clear} = E_0 \cos(\theta_s) T_d T_g$ is the solar flux that would reach the surface if the cloud/surface system were non reflecting and non-absorbing.

-In clear sky conditions, A reduces to A_s.

Algorithm

-In order to compute E, A is expressed as a function of the radiance measured by the ocean-color sensor in the PAR spectral range. This includes:

(1) converting the TOA radiance into reflectance,

(2) correcting the TOA reflectance for gaseous absorption and scattering by the atmosphere/surface system, and

(3) transforming the corrected reflectance into albedo.

Procedure

-A daily PAR estimate is obtained for each instantaneous pixel, assuming the cloud/surface system is stable during the day and corresponds to the satellite observation.

-Daily PAR estimates obtained separately from different orbits and individual sensors are binned using a simple, linear averaging scheme (arithmetical mean), or by weighting the estimates using the cosine of the solar zenith angle.

-Since MODIS-Terra, SeaWiFS, and MODIS-Aqua cross the Equator at different local times (i.e., 10:30, 12:00, and 13:30) the diurnal variability of clouds is taken into account by averaging individual estimates.

-To ensure consistency of the PAR data over time, estimates using data from one, two, or three sensors are compared, and statistical adjustment factors determined.

-The procedure has been used to generate the operational SeaWiFS PAR product. It has been adapted to POLDER, GLI, MODIS, and MERIS.

3. EVALUATION

-The SeaWiFS PAR algorithm/product has been evaluated against in situ measurements from the COVE platform off the west coast of the US (2 PAR sensors, 36.90N-75.71W).

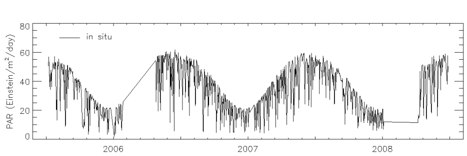

***Figure 1**: Time series of daily surface PAR measured in situ (average of data from 2 PAR sensors) at the COVE site. (The COVE Team is gratefully acknowledged for maintaining the PAR sensors and making the data available.)*

***Table 1**: Comparison statistics of estimated and measured surface PAR at the COVE site for daily, weekly, and monthly time scales. All situations (clear and cloudy) are used in the comparisons.*

Satellite(s)	Daily	Weekly	Monthly
SeaWiFS	r^2 = 0.874 Bias = 2.83 E/m^2/d RMS Diff. = 6.49 E/m^2/d Nb. Points = 1408	r^2 = 0.931 Bias = 2.65 E/m^2/d RMS Diff. = 4.54 E/m^2/d Nb. Points = 225	r^2 = 0.968 Bias = 2.25 E/m^2/d RMS Diff. = 3.30 E/m^2/d Nb. Points = 57
MODIS-Aqua	r^2 = 0.857 Bias = 1.85 E/m^2/d RMS Diff. = 6.77 E/m^2/d Nb. Points = 1582	r^2 = 0.932 Bias = 1.88 E/m^2/d RMS Diff. = 4.22 E/m^2/d Nb. Points = 265	r^2 = 0.977 Bias = 1.77 E/m^2/d RMS Diff. = 2.85 E/m^2/d Nb. Points = 63
MODIS-Terra	r^2 = 0.883 Bias = 2.31 E/m^2/d RMS Diff. = 6.28 E/m^2/d Nb. Points = 1596	r^2 = 0.945 Bias = 2.33 E/m^2/d RMS Diff. = 4.25 E/m^2/d Nb. Points = 265	r^2 = 0.983 Bias = 2.27 E/m^2/d RMS Diff. = 3.23 E/m^2/d Nb. Points = 63

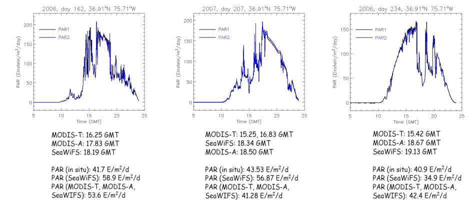

***Figure 2**: Measured surface PAR in typical cloudy situations at the COVE site. Combining estimates from three instruments reduces the differences with in situ measurements.*

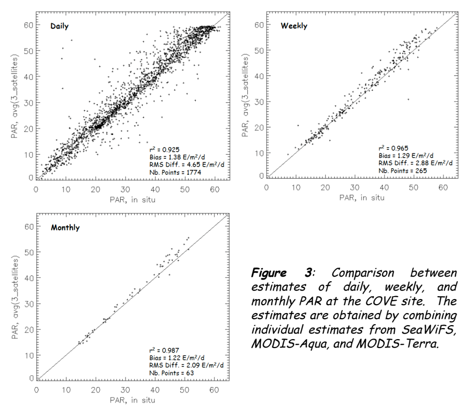

***Figure 3**: Comparison between estimates of daily, weekly, and monthly PAR at the COVE site. The estimates are obtained by combining individual estimates from SeaWiFS, MODIS-Aqua, and MODIS-Terra.*

-Using three satellites, the performance is improved compared with that of individual satellites, with biases and RMS differences in monthly values reduced to 1.2 and 2.9 E/m^2/d, respectively (see Table 1 for comparison).

-The remaining biases are likely due to the diurnal variability of cloudiness not fully accounted for in the algorithm. At the COVE site, a maritime non-convective location, cloud cover tends to be higher in the morning and afternoon, and the times of satellite overpass are generally in the middle of the day.

4. GENERATION OF A CONSISTENT LONG-TERM RECORD

-The PAR values from individual instruments were compared with those from combining three instruments. Monthly maps of average differences were computed at 9 km resolution. These maps were then used to correct the estimates from individual instruments and produce a 13-year time series of PAR imagery from 1997 to 2010.

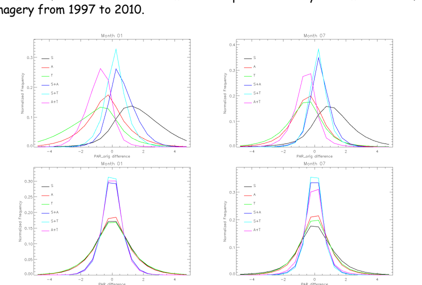

***Figure 4**: (Top) Histograms of January and July differences between PAR (in E/m^2/d) derived by one or two instruments and by three instruments. (Bottom) Same as Top, but after correction of biases. The histograms are computed with global PAR data from January 2005 to December 2010.*

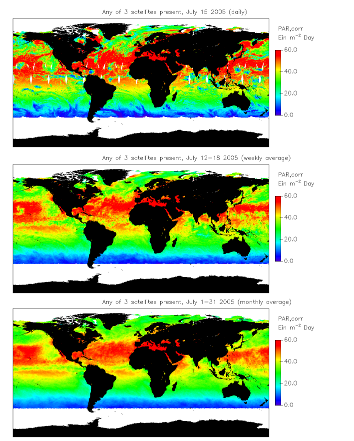

***Figure 5**: Example of daily, weekly, and monthly PAR products computed from SeaWiFS, MODIS-Aqua, and MODIS-Terra (all available instruments are used). Data from individual instruments are corrected for biases with respect to three instruments. (Top) July 15, 2005. (Middle) July 12 to 18, 2005. (Bottom) July 2005.*

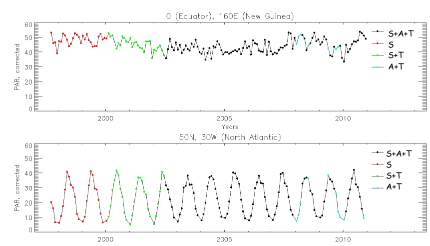

***Figure 6**: Time series of monthly PAR data obtained from one, two, or three instruments. (Top) Equator, 160 E. (Bottom) 50 N, 30 W. The values obtained by individual instruments are corrected for biases with respect to three instruments.*

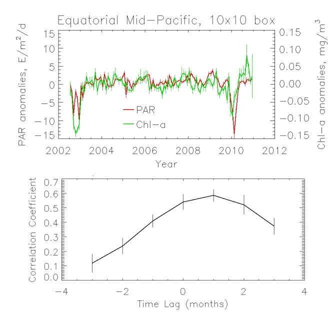

***Figure 7**: (Top) Monthly PAR and [Chl-a] anomalies in the Central Equatorial Pacific (170W) during 2002-2011. (Bottom) Lagged linear cross-correlation coefficient between PAR and [Chl-a] anomalies. The PAR anomalies tend to lag the [Chl-a] anomalies by a month, suggesting that fluctuations in PAR may not be a driving force behind the [Chl-a] changes.*

5. CONCLUSIONS

-A global, 13-year record of PAR at the ocean surface (9-km resolution) has been generated from SeaWiFS, MODIS-Aqua, and MODIS-Terra data.

-Observations by individual instruments, combinations of two instruments, and three instruments are considered in the calculations.

-Spatial and temporal biases between estimates from one, two, or three instruments are determined and corrected, resulting in a consistent time series for variability studies.

-Uncertainties are quantified on daily, weekly, and monthly time scales for the various instrument combinations from comparisons with in situ measurements. They indicate that the PAR products are suitable for large-scale studies of aquatic photosynthesis.

-PAR monitoring will continue with current and future satellite ocean-color sensors, and the methodology will be extended to generating UV-A and UV-B irradiance.